THE HIGH ECCENTRICITY

OF THE PLANET AROUND 16 CYG B

Tsevi Mazeh, Yuval Krymolowski and Gady Rosenfeld

School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences,

Tel Aviv University, Tel Aviv, Israel

mazeh@wise7.tau.ac.il

Version of Nov. 12th, 1996

ABSTRACT

We consider the high eccentricity, 0.66, of the newly discovered planet around 16 Cyg B, using the fact that the parent star is part of a wide binary. We show that the high eccentricity of the planet could be the result of tidal forces exerted on 16 Cyg B and its planet by 16 Cyg A, the distant companion in the system. By following stellar triple systems with parameters similar to those of 16 Cyg, we have established that the orbital eccentricity of the planet could have gone through strong modulation, with an amplitude of 0.8 or even larger, with typical timescale of tens of millions years.

The amplitude of the planet eccentricity strongly depends on the relative inclination between the plane of motion of the planet and that of the wide binary 16 Cyg AB. To account for the present eccentricity of the planet we have to assume that the angle between the two planes of motion is large, at least 60°. We argue that this assumption is reasonable for wide binaries like 16 Cyg AB.

1. INTRODUCTION

Very recently, Cochran et al. (1996) have announced the discovery of a new extra-solar "planet-candidate", with minimum mass of 1.5 Jupiter masses, orbiting 16 Cyg B. The new planet has two special features. The first one is its orbital eccentricity, 0.66, which is remarkably larger than the eccentricities of all other seven planets with a minimum mass smaller than 10 Jupiter masses (e.g. Boss 1996). The other feature is the existence of another star, 16 Cyg A, near the parent star of the planet, with a separation of about 40 arcsec. The proper motion and the radial-velocity of 16 Cyg A and B (HR 7503 and HR 7504) are very close to each other (Hoffleit & Jaschek 1982), so there is no doubt that the two stars are physically connected.

Both features are very intriguing. Prior to the discovery of 16 Cyg B planet, Mazeh, Mayor & Latham (1996) pointed out that the other seven "planet-candidates" display a correlation between their masses and orbital eccentricities. Companions with masses smaller than about 5 Jupiter masses have circular orbits while the more massive companions have eccentric orbits. The new planet, with its low mass and high eccentricity, breaks this pattern. The other feature, the existence of the distant companion, 16 Cyg A, demonstrates for the first time that a planet with a long period (P=804 days) can be formed in a binary system. In this very short note we suggest that the two features of the new planet *might* be correlated.

Mazeh & Shaham (1979) have shown that in hierarchical stellar triple systems, the third distant star which orbits the close binary can, in many cases, modulate the inner binary eccentricity. This comes from the fact that the simple-minded model of hierarchical triples is only a first-order approximation. This model assumes that the motion of the three bodies can be composed of a Keplerian motion of an inner pair and another Keplerian motion of the center of mass of the inner pair and the distant star. However, the gravitational attraction

of the tertiary exerted on the two inner bodies is different from the attraction exerted on a body at the center of mass of the inner binary system. The difference, sometimes referred to as the tidal force of the third star, can induce long-term slow modulation of the inner binary eccentricity. We will show here that the high eccentricity of the planet around 16 Cyg B could have resulted from the tidal forces of 16 Cyg A — the distant component of the system.

At a distance of 26 pc, the projected separation between 16 Cyg A and B is about 1000 AU, a lower limit to the actual present separation. The semi-major axis could be smaller or larger than the present separation, depending on the eccentricity and the phase of the wide orbit. Somewhat arbitrarily, we assume here that the semi-major axis of the wide binary is 1100 AU. The semi-major axis of the planet-candidate around B is 1.7 AU (Cochran et al 1996). We get therefore an hierarchical triple system with semi-major axis ratio of about 650. This is a relatively large ratio, considering the fact that some known triples display semi-major axis ratio of the order of ten (Fekel 1981, Tokovinin 1996).

The large semi-major axis ratio makes the system of 16 Cyg very stable, and turns the tidal forces of A exerted on B and its planet to be very small. One might think therefore that the amplitude of the planet eccentricity modulation is small. This intuition is wrong. It is true that the smallness of the tidal forces makes the variation of the planet eccentricity very slow. However, another effect of the smallness of the tidal forces of the distant star is to make the period of the eccentricity modulation very long. Thus, the total increase of the planet eccentricity, which is being accumulated for a long period of time, can be very large, and is only weakly sensitive to the semi-major axis ratio of the system. We will present here simulations which will demonstrate that in some cases an initial small eccentricity, of, say 0.15, can grow by the tidal forces of the distant star up to 0.8, with a modulation period of the order of 10 million years.

2. THE MODULATION OF THE INNER BINARY ECCENTRICITY

To study the possible configurations which might display a dramatic modulation of the eccentricity of the planet of Cyg 16 B we treated the whole system as a triple stellar system, in which the inner binary consists of 16 Cyg B and its planet, while the tertiary is 16 Cyg A. We denoted the masses of 16 Cyg B and its planet as m_1 and m_2, respectively, while the mass of A will be denoted by m_3.

The large ratio of the semi-major axes of the two orbits makes the period of the inner eccentricity modulation very long. Mazeh & Shaham (1979), using a third-order Hamiltonian of the three-body problem (Harrington 1968, 1969) estimated the modulation period to be

$$P_{mod} \sim P_3 \Big(\frac{P_3}{P_{1,2}} \Big) \Big(\frac{M}{m_3} \Big) \, ,$$

where P_3 is the third star orbital period, $P_{1,2}$ is the close binary period and M is the total mass of the binary system. Assuming m_1, m_2 and m_3 to be 1, 0.0016 and 1.03 $M_\odot$, respectively (Cochran et al. 1966), $P_{1,2}$ and P_3 to be 2.2 and 25,000 yrs, respectively, we get P_{mod} of the order of $3\,10^8$ yrs, or 100 million inner orbit revolutions.

To directly integrate Newton equations of the three body problem for 100 million inner revolutions we need days, if not weeks, of CPU time, even with the fastest available computers. The long CPU time needed does not allow to search extensively the possible parameter space of triple system for configurations which display large inner eccentricity modulation. In particular, we wanted to follow the inner eccentricity evolution for configurations with different relative angles between the two orbital motions and different outer eccentricities. We therefore had to use some approximation to the three body problem which would enable us to study the characteristics of the inner eccentricity modulation.

Fortunately, such an approximation has been already developed and was available for following long-term modulation of triples like the 16 Cyg system.

2.1.   Third-Order Approximation

The approximation theory we used is based on Harrington's (1968, 1969) approach, in which the Hamiltonian of the triple system is expanded into an infinite series with respect to a small parameter — the ratio of the semi-major axis of the inner orbit to that of the outer orbit. Mazeh & Shaham (1979) used the third-order Hamiltonian to deduce the approximate time derivative of $e_{1,2}$, the inner binary eccentricity, which varies with $g_{1,2}$, the longitude of periastron of the inner binary. Moreover, Mazeh & Shaham were able to show that within the third-order approximation the variation is cyclic and the modulation is therefore periodic.

Mazeh and Shaham derived explicitly the time derivative of the inner eccentricity only for small $e_{1,2}$. Following their approach we derive the full third-order equations to be:

$$\frac{de_{1,2}}{dt} = \frac{2\pi}{P_{mod}} \frac{15}{8} \frac{\sqrt{1-e_{1,2}^2}}{(1-e_3^2)^{3/2}} (1-\Phi^2) e_{1,2} \sin 2g_{1,2}$$

$$\frac{dg_{1,2}}{dt} = \frac{2\pi}{P_{mod}} \frac{3}{8} \frac{1}{(1-e_3^2)^{3/2}}$$
$$\times \left[(G-\Phi) \frac{\Phi(2+3e_{1,2}^2 - 5e_{1,2}^2 \cos 2g_{1,2})}{\sqrt{1-e_{1,2}^2}} + \sqrt{1-e_{1,2}^2} \left((3\Phi^2 - 1) + 5(1-\Phi^2) \cos 2g_{1,2} \right) \right]$$

where

$$G = \frac{m_1 m_2}{m_3(m_1+m_2)} \sqrt{\frac{m_1+m_2+m_3}{m_1+m_2} \frac{a_{1,2}}{a_3} \frac{1-e_{1,2}^2}{1-e_3^2}} ,$$

$\Phi = \cos\Theta$, and $a_{1,2}$ and a_3 are the semi-major axes of the inner and the outer orbit, respectively. These equations are faster to integrate than Newton equations by a few orders of magnitude.

The ratio of the semi-major axis of the inner orbit to that of the outer motion for the 16 Cyg system is 1/640, small enough to suppose that the third-order approximation does reflect the actual variation of the inner binary eccentricity. To make sure this is the case for the 16 Cyg system, we used a very recent study of the fourth-order approximation to the three body problem (Krymolowski 1995; Krymolowski & Mazeh 1996). For all cases that we checked, with large angle between the two planes of motion, the fourth-order approximation did confirm the modulations derived by the third-order equations.

Further, we also compared the third-order approximation of two cases with direct numerical integration of Newton equations. We ran the code of Charles Bailyn (1987) who uses the Bulirsch-Stoer integration scheme. With a precision parameter of 10^{-11} per integration step, we get relative energy error of about 10^{-4} for the whole integration, which included $2\,10^7$ inner revolutions. The code ran on a Silicon Graphics Power Challenge 10000, with MIPS R10000 running at 200MHz as CPU. Despite the extremely fast machine, a *week* of CPU time was enough to follow the triple system only for 20 million inner revolutions. However, for this period of time the result of the direct numerical integration also confirmed the third-order approximation for the two cases.

Further, we ran another code which follows a test particle in a binary system by integrating Newton equations with the Bulirsch-Stoer scheme. The code followed the test particle for 100 million inner revolutions and yielded similar results. All these checks convinced us that the third-order approximation does describe correctly the inner eccentricity modulation.

In Figure 1 we present two simulations which compare the third-order approximation with the direct integration. In both cases, the angle between the inner and outer planes of motion, Θ, is 60°. The only difference between the two simulations is the outer eccentricity, e_3, which is equal to 0.85 in one case and is equal to 0.60 in the other case. In both cases

the initial value of $g_{1,2}$ was 60° and that of g_3 10°. The third-order approximation was run for 200 million inner revolutions, while the direct integration of Newton equations goes only for 20 million revolutions.

The aim of bringing these two cases is two folded. We first wish to show how good is the third-order approximation for the 16 Cyg system for configurations with high relative inclinations. Indeed, the direct integration follows exactly the third-order approximation. Secondly, the figure demonstrates that the inner eccentricity can grow from 0.15 to 0.66 and larger, solely as a result of the tidal force of the third star.

2.2. The Amplitude of the Inner Eccentricity Modulation

Having established the applicability of the third-order approximation for the 16 Cyg system, we have used this approximation for an extensive study of the inner eccentricity modulation as a function of the different parameters of the triple system. It turned out that the amplitude depends mainly on Θ, as pointed out already by Söderhjelm (1982). To demonstrate this point we followed Söderhjelm and calculated the maximum of the inner eccentricity as a function of Θ for the 16 Cyg system. The results of these calculations are plotted in Figure 2 for $e_3 = 0.85$. The Figure shows different curves for different initial conditions of $e_{1,2}$. We see that the maximum eccentricity rises sharply at about $\Theta = 40°$, and that for relative angle close to 90° we can even get inner eccentricity close to unity.

One word of caution is due here. For small value of Θ Figure 2 shows that the maximum inner eccentricity is rather small and insensitive to Θ. However, this is an artifact of the third-order approximation. Fourth-order approximation and the direct integration of newton equations show that in those cases the next term of the series of expansion of the Hamiltonian is more important and it contributes substantially to the inner eccentricity

modulation (Krymolowski 1995; Krymolowski & Mazeh 1996). However, above 40° the third-order approximation becomes very accurate, as demonstrated in Figure 1.

3. Discussion

By following stellar triple systems with parameters similar to those of 16 Cyg, we have established that the orbital eccentricity of the planet around 16 Cyg B could have gone through strong modulation because of the the tidal forces of 16 Cyg A. The modulation period of the inner eccentricity of 16 Cyg B is of the order of 100 million years. This period is short relative to the circularization timescale of the planet, because of its relatively long orbital period. Therefore, the tidal interaction of 16 Cyg A can modulate freely the inner eccentricity.

The planet of 16 Cyg B is probably not the only known planet in wide binary. It seems as if three other planets, the ones around 55 Cnc, υ And and τ Boo, might reside in wide binaries (Marcy, private communication). However, the planets of those systems have very short orbital periods, and therefore the circularization timescale is shorter than the inner eccentricity modulation period. Therefore, even if the orbital plane of the planet is highly inclined relative to the wide binary orbit, the circularization processes prevent the inner eccentricity from growing.

The simulations have shown that the modulation of the eccentricity of the planet strongly depends on the relative inclination between the two planes of motion. Therefore, if the present eccentricity of 0.66 is indeed the result of the tidal forces of 16 Cyg A, we have to assume that the angle between the two planes of motion is large, at least 60°.

Let us assume that the orbital motion of the planet is aligned with the stellar rotation of 16 Cyg B. This is very probably the case if the planet was formed from a disc around 16

Cyg B. Such a disc was aligned along the angular momentum of the protostar, and so did the spin of 16 Cyg B. Therefore, the question whether a large angle between the orbital motions of the planet and the motion of the wide binary is possible comes down to the question of alignment between the stellar rotation and the orbital angular momentum of the wide binary.

A study on exactly this issue has been published recently. Hale (1994) examined a sample of nearby solar-type stars in binaries and checked the tendency for alignment between the stellar spin and the orbital angular momentum. He found such tendency only for binaries with separation less than 30-40 AU. He did *not* find any tendency for binaries with larger separations. If we accept Hale's findings, we can safely *assume* that the rotational axis of 16 Cyg B is not aligned with the orbital angular momentum of A and B, and further *assume* that the orbital plane of the planet is also inclined to the the orbital plane of A and B. The last assumption can explain the high eccentricity of the "planet candidate".

Is there any observational test, in the present or in the near future, to confront our suggestion with the observations? We cannot think of any such test in the foreseen future. The long period of A and B turns the finding of the exact orientation of the wide binary hopeless within human lifetime. Thus, there is no hope to measure or estimate the relative angle between the two motions, even if we measure the inclination of the planet's orbit relative to our line of sight. The modulation period of the eccentricity of the planet is even longer, of the order of 10 million years, and therefore there is no hope to detect the planet eccentricity variation in the near future. It seems therefore that the relative angle between the two motions will stay under the cover of clouds of doubts for a long time.

However, the question whether there exists a correlation between the mass and the orbital eccentricity of the extra-solar planets probably will be settled in the near

future. The rate of announcements of newly discovered planets in 1996 is about 0.5 PPM (=Planet Per Month). If this rate will be kept constant for a few years, we will have soon a large sample of planets, and we will then be able to decide whether this correlation is a true feature of the extra-solar planets.

References

Bailyn, C. D. 1987, PhD thesis, Harvard University

Boss, A.P. 1996, Physics Today, Sept. 1996, 32

Cochran, W.D., Hatzes, A.P., Butler, R.P. & Marcy, G.W. 1996, Abstract of a paper presented at the DPS/AAS October meeting

Fekel, F.C. 1981, ApJ, 246, 879

Hale, A. 1994, AJ, 107, 306

Harrington, R. S. 1968, AJ, 73, 190

Harrington, R. S. 1969, Celes. Mech., 1, 200

Hoffleit, D. & Jaschek, C. 1982, Bright Star Catalogue (4th revised version) (New Haven: Yale Univ. Observatory)

Mazeh, T., Mayor, M. & Latham, D.W. 1996, ApJ, in press

Mazeh, T. & Shaham, J. 1979, A&A, 77, 145

Söderhjelm S. 1982, A&A, 107, 54

Tokovinin, A.A. 1996, A&A, submitted

Fig. 1.— The inner binary eccentricity as a function of time. The continuous line is the result of direct integration of Newton equations, while the crosses are the results of the third-order approximation. See text for details.

Fig. 2.— The maximum of the inner eccentricity as a function of the relative inclination between the two orbital motion. The outer eccentricity is 0.85.